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DEVELOPMENT OF SUPERCONDUCTING-CAVITY STABILIZED OSCILLATORS FR--ETC(U)
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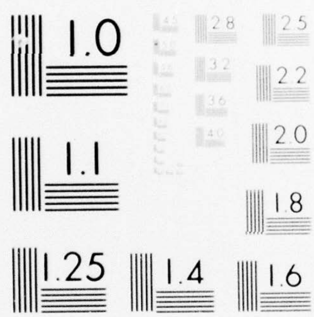

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6 Development of Superconducting-Cavity Stabilized Oscillators from 1971-1977.

9 FINAL REPORT. Apr 71 – Mar 77.

TO THE OFFICE OF NAVAL RESEARCH

15 CONTRACT N00014-76-C-0382

12 11p.

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FINAL REPORT TO THE OFFICE OF NAVAL RESEARCH

FOR CONTRACT N00014-76-C-0382

Contract N00014-76-C-0382 and its predecessor, contract N00014-67-A-0112-0087, were for the development of superconducting-cavity stabilized oscillators for the period from October 1974 to March 1977. Development of superconducting-cavity oscillators was also done under earlier Office of Naval Research Contracts N00014-67-A-0112-61 and N00014-67-A-0112-0076, which covered the period from April 1971 to March 1974. The work on the development of superconducting-cavity stabilized oscillators was a small part of the work under these earlier contracts. This final report includes a summary of what was accomplished under these contracts from April 1971 to March 1977, a brief description of current SCSO performance and a conclusion.

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DEVELOPMENT OF SUPERCONDUCTING-CAVITY

STABILIZED OSCILLATORS FROM 1971 to 1977

Superconducting cavities had been investigated as frequency determining elements of oscillators prior to when our work began at Stanford in 1971. Most of that work had been done at the Institute of Fundamental Electronics at the University of Paris at Orsay under the direction of Professor Septier. Although they successfully tested a number of oscillator techniques using a superconducting cavity as the frequency reference, the stability of these oscillators were limited to about $10^{-11}(\delta f/f)$ for short term frequency fluctuations. 10 to the -11th power (delta f/f)

At Stanford, we estimated that a very high frequency stability of $10^{-16}(\delta f/f)$ 10 to the -16th power (delta f/f) should be possible using superconducting niobium cavities with an unloaded Q of 10^{11} 10 to the 11th power along with available experimental techniques. Unloaded Q's of 10^{11} had already been demonstrated at Stanford for superconducting niobium cavities. To achieve an oscillator utilizing a superconducting cavity, we designed a circuit which stabilizes a Gunn oscillator at X-band to a superconducting cavity at 8.6 GHz . We called this oscillator system a superconducting-cavity stabilized oscillator (SCSO). Our first test showed that this circuit worked satisfactorily and a short-term frequency stability of $10^{-12}(\delta f/f)$ was achieved. 10 to the -12th power (delta f/f)

The development work on the SCSO proceeded in a number of steps after the SCSO circuit was shown to work satisfactorily. Much of the development

work at Stanford has been reported in the references given in the bibliography. Two papers on this work remain to be completed.

In the first step, a system of two SCSO's was constructed. With this system, the sensitivity of the superconducting cavity frequency with respect to cavity temperature, cavity stored energy, cavity tilt in the gravitational field, cavity mechanical vibrations and radiation incident on the cavity were measured. At the same time, the electronic instrumentation for both the SCSO circuit and for the frequency stability measurements were built and improved. With this system of SCSO's, the short-term frequency fluctuations were reduced to 10^{-14}.

In the second step, a system of three independent SCSO's was constructed. The design of this system used the experience gained with the system of two SCSO's to make improvements which would lead to greater frequency stability. In addition, the cryogenic system was designed so the SCSO's could be operated for a longer period of time, between two and three weeks. A system of three independent SCSO's also allowed one for the first time to measure the short-term frequency fluctuation of an individual SCSO. This made it possible to study the effect of unloaded Q and cavity construction on short-term frequency stability. With this system of three SCSO's, the short-term frequency fluctuations were reduced to 10^{-15}. Also, the SCSO's long-term frequency drift relative to Cs frequency standards was measured to be typically $\pm 2 \times 10^{-13}$ day^{-1}.

The final step of development of the SCSO at Stanford was to isolate the system of three SCSO's as much as possible from ambient conditions as well as record important ambient conditions during SCSO operation. The system of three SCSO's was moved to a new laboratory whose floor had a much

lower level of tilt and vibration. The SCSO was surrounded by a room for temperature control and to reduce air propagated vibration. A digital recording system was designed and built which periodically recorded SCSO ambient conditions including the two axis tilt of the cryogenic system, helium vapor pressure, room temperature and temperatures at various locations of the SCSO system. With these improvements, short-term frequency stabilities of 3×10^{-16} were observed, which is very near the value estimated at the beginning of this development work. The SCSO's long-term frequency drift relative to the Cs frequency standards was reduced to typically $\pm 1 \times 10^{-14}$ day^{-1} . The ambient condition data collected during operation of the SCSO's is still being analyzed.

SCSO PERFORMANCE

The SCSO has been developed to the point where it has exceptionally high frequency stability and for some conditions it rivals or exceeds other state-of-the-art frequency sources. The spectral density of phase fluctuations, Allan variance and long-term frequency drift are discussed below.

Spectral Density of Phase Fluctuations. The SCSO has not been optimized to reduce the spectral density of phase fluctuations since doing that would degrade the longer term performance of the SCSO. Nevertheless, the SCSO has exceptionally low phase fluctuations as is shown in Fig. 1 for an SCSO at 8.6 GHz . S_φ is very low at the level of 1×10^{-12} $\mathrm{radians}^2 - \mathrm{Hz}^{-1}$ for frequencies between 100 Hz and 50 kHz . This level of S_φ is limited by noise introduced by the crystal detector in the SCSO circuit. Below 500 Hz there are a number of peaks in S_φ which appear to be bright lines associated with mechanical vibrations coupled to the cavity. The width of these lines

appears to be much narrower than the 3 Hz bandwidth of the spectrum analyzer. The peak in S_φ at about 300 kHz is associated with the frequency response of the SCSO feedback loop, while the general decrease in S_φ above 700 kHz is due to the bandwidth of the Gunn oscillator cavity.

Allan Variance. The Allan variance for an SCSO is shown in Fig. 2 as a function of sampling time τ . For $\tau \leq 10$ s , a typical SCSO has an Allan variance of $\sigma_y = 1 \times 10^{-14}/\tau$. For longer times, the Allan variance depends on the unloaded Q and coupling factor for the superconducting cavity with the highest Q cavities giving the lowest σ_y . In the latest tests, SCSO #3 has the cavity with the highest unloaded Q which is 6×10^{10} , and the oscillator indeed has the lowest σ_y . This oscillator has a noise floor of $\sigma_y = 3 \times 10^{-16}$ for τ between 30 and 1000 s . For $\tau > 1000$ s , σ_y increases because of the long-term frequency drift of the SCSO.

Long-Term Frequency Drift. Figure 3 gives an example of the time difference between the three SCSO's (operated as clocks) and a Cs atomic clock as a function of elapsed time for nine days. The fractional frequency drifts of the three SCSO's relative to the Cs frequency standard may be determined from the data in the figure and are 3.6×10^{-15} , -2.0×10^{-15} and 18.1×10^{-15} day^{-1} . Several such long-term drift measurements have been made for the three SCSO's and the fractional frequency drift is typically $\pm 1 \times 10^{-14}$ day^{-1} .

CONCLUSION

The superconducting-cavity stabilized oscillator has been greatly advanced in performance as a result of the work under the office of Naval Research Contracts. The noise floor of the spectral density of phase fluctuations for the SCSO is very low, and it is currently about a decade below that for crystal oscillators optimized for this characteristic. The noise floor of the Allan variance for the SCSO $\sigma_y = 3 \times 10^{-16}$ extends over sampling times from 30 to 1000 s , and it is currently substantially lower than state-of-the-art hydrogen MASERS which have a σ_y of about 1×10^{-15} for sampling times of greater than a few hundred seconds. The fractional frequency drift rate of the SCSO's is typically $\pm 1 \times 10^{-14}$ day^{-1}, which although not as low as a hydrogen MASER or Cs frequency standard is nonetheless exceedingly low when compared to a crystal oscillator.

Further performance improvements in the SCSO may be expected if development work is continued. The spectral density of phase fluctuations may be improved perhaps several decades by using a different oscillator circuit employing a superconducting cavity, such as the one being investigated by S. R. Stein at NBS, Boulder, CO. The noise floor in the Allan variance for the SCSO may be improved a decade to $\sigma_y = 3 \times 10^{-17}$ by both increasing the superconducting cavity Q and improving the SCSO feedback electronics. Finally, the long-term frequency drift of the SCSO may be improved a substantial but unknown amount by both reducing tilt by use of feedback and by improving the mechanical aspects of the cryogenic system. Also, flying an SCSO in a satellite may reduce drift substantially since the large reduction in gravitational acceleration would reduce the importance of tilt.

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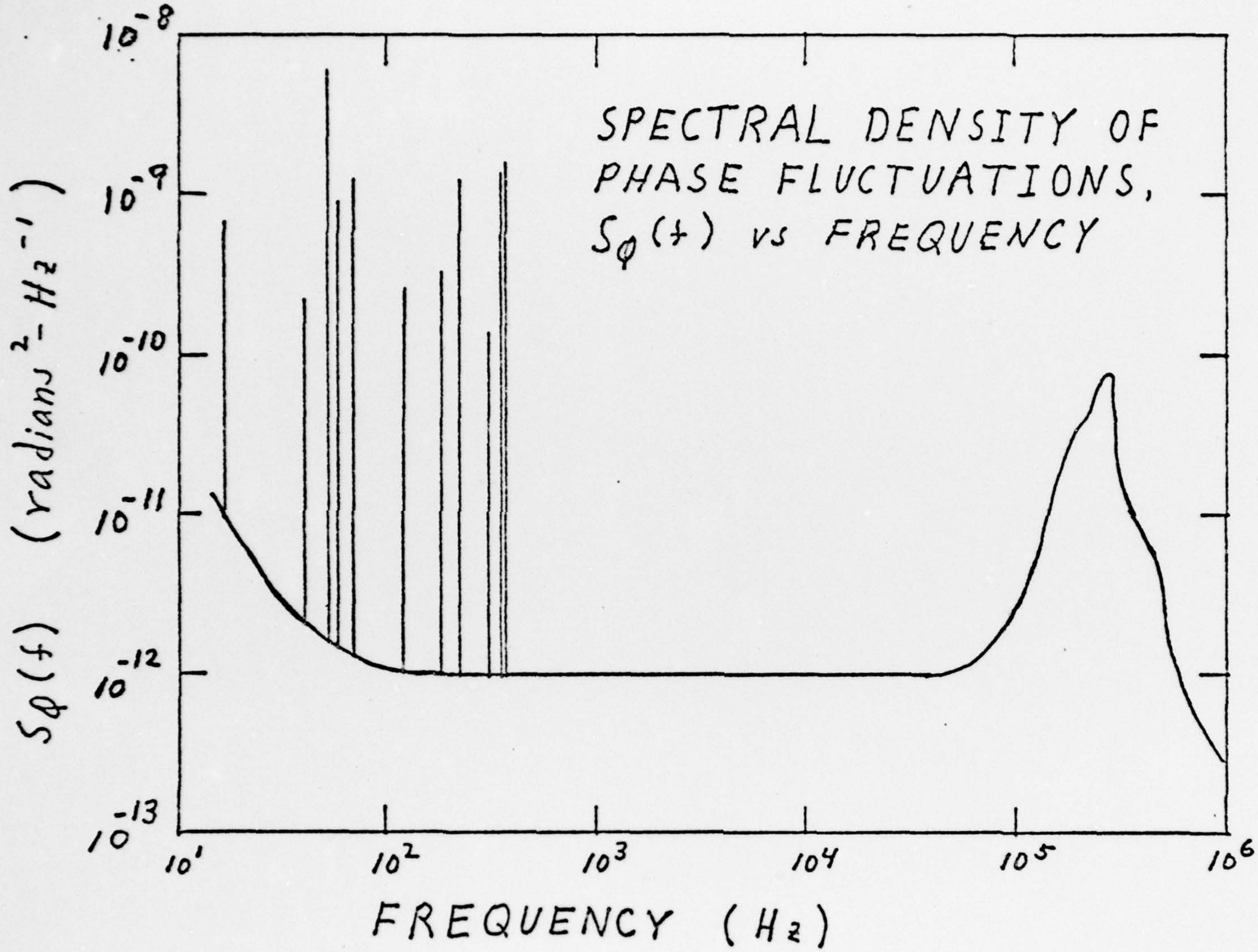

Fig. 1--Spectral Density of Phase Fluctuations Versus Frequency for a SCSO.

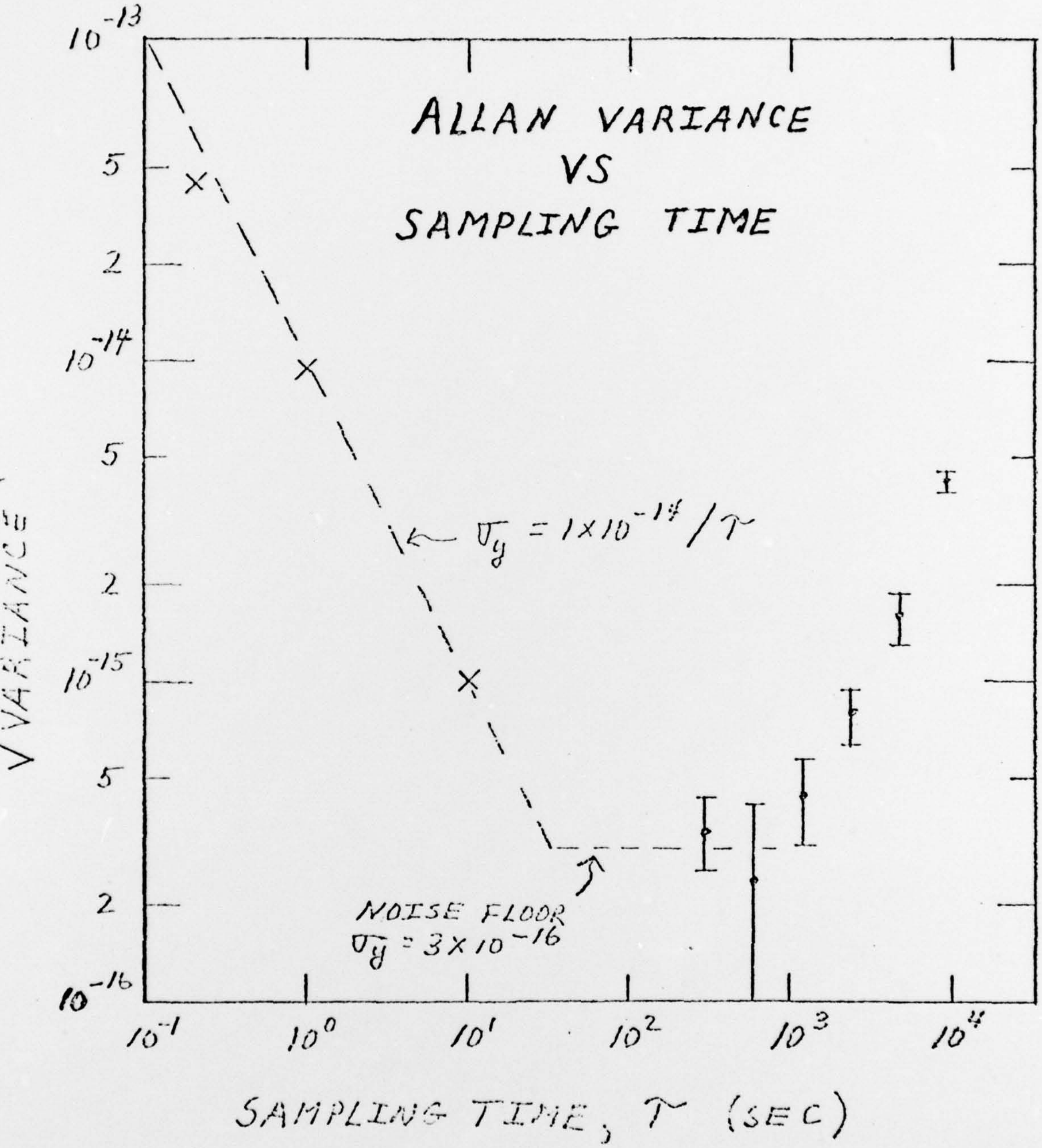

Fig. 2--Allan Variance Versus Sampling Time for an SCSO. Data points typical of all three SCSO's for $\tau \leq 100$ s are represented by crosses, and data points for SCSO #3 ($\tau \geq 300$ s) are represented by dots and error bars.

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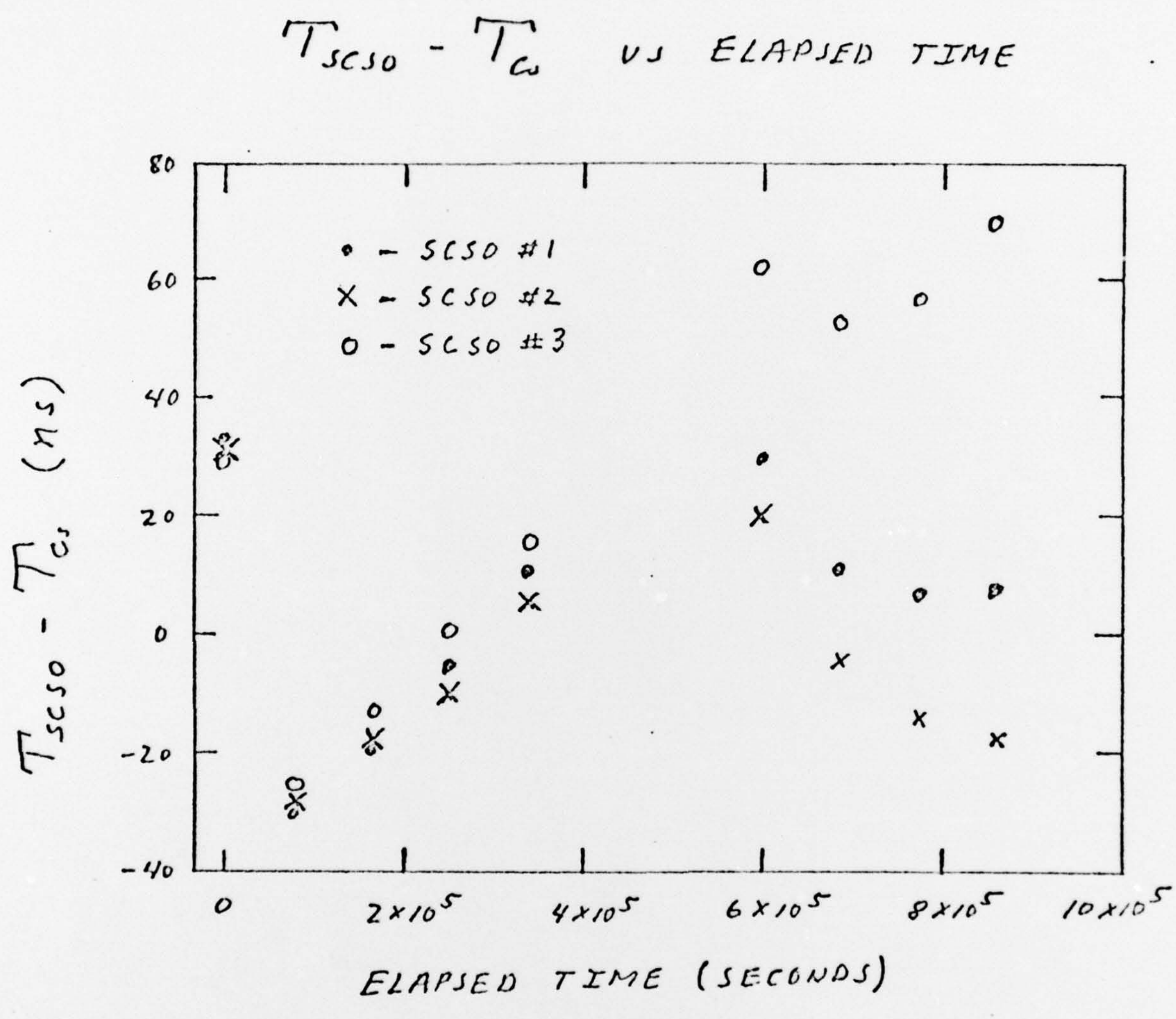

Fig. 3--Time Difference between SCSO Time and Cs Atomic Time Versus Elapsed Time.